

ACOUSTIC EMISSION WAVEFORM ACQUISITION DURING FATIGUE CRACK GROWTH

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INTRODUCTION

In this paper a PC based acoustic emission system is described which is capable of digitally acquiring acoustic emission waveforms and environmental parameters for a component under load. In addition experimental results are presented that illustrate the advantages and capabilities of such a system.

Stress waves produced by crack growth, are frequently detectable as acoustic emissions. Acoustic emission (AE) monitoring is extremely sensitive, and can be used to detect very small damage processes such as microindentation cracking, with crack sizes in the order of microns [1]. AE event monitoring can be used in situ to obtain information about the existence or progression of damage in a material, and is ideally suited to monitoring components where access is difficult, critical flaw sizes are small, or where inspection by standard techniques is otherwise hindered.

However, acoustic emission from damage progression is not necessarily the only sound source observed in a component. Mechanical vibrations, rubbing of adjacent surfaces, and hydraulic noises are benign sound sources in physical systems. Electrical interference can also generate false events. The ability to discriminate between damage-related and benign events is the determining factor in how useful this technique can be for in-service component monitoring. Because early detection of cracking events relies on the use of a very high sensitivity data acquisition system, detection of benign events also tends to be maximized. It is therefore necessary to eliminate the benign events from consideration to avoid false calls. For example, if AE monitoring is used to replace regularly scheduled maintenance inspections on a component, the part would then only be inspected if incipient cracking were indicated by the monitoring system. A high incidence of false calls from such a system could conceivably result in a greater amount of inspection and component down time than that used for periodic maintenance.

Several techniques can be employed to minimize such false calls. By using multiple sensors, the source of emissions can be localized and signals generated outside a region of interest can be eliminated based on relative arrival times. Signal processing techniques, on the other hand, employ the concept that sounds from different sources differ in their waveform characteristics to provide source discrimination. Standard acoustic emission systems use relatively rapid and simple analog and digital techniques to acquire waveform parameters such as amplitude, duration, frequency, and energy. It is

still difficult, however, to make decisions based on this limited information. The signals from cracking and part surfaces rubbing against each other can be particularly difficult to separate using this information. A bolted component can contain both of these sources; the parts can move relative to one another, and/or a crack can originate from a fastener hole.

Another technique for event discrimination looks at the load at which an event occurs. Under tension fatigue conditions, crack extension occurs at high loads. Furthermore, in the absence of inertial effects, extension occurs on rising load rather than falling load [2]. Such load environment information can thus be used to isolate regions in the load cycle where it is likely that crack advance will occur. In controlled experiments, this information can be used to isolate characteristic crack signals which can be used as sample data sets required in the development of signal processing algorithms. In real part monitoring, load environment (more likely obtained in this case from strain gages or accelerometers) can be used as a weight factor in the signal discrimination process.

The acoustic emission monitoring system described in this paper acquires and stores time-domain waveforms. This allows for detailed examination of the signal characteristics and for adaptive processing of the information in an attempt to obtain robust source discrimination techniques. The acquisition system also has the ability to take advantage of environmental parameters such as the load the component sees at the time of the event to aid in signal characterization.

The equipment has been tested in the laboratory on aluminum lithium and aluminum fatigue crack growth specimens. The ability to acquire and store time domain acoustic emission waveforms as well as load environment information in real time has been demonstrated. In addition, preliminary signal processing algorithms have been developed to separate event sources.

EQUIPMENT CHARACTERISTICS

The acoustic emission monitoring system used for these studies is PC-based, and utilizes 2 expansion boards. The first board is used for rapid digitization of the acoustic

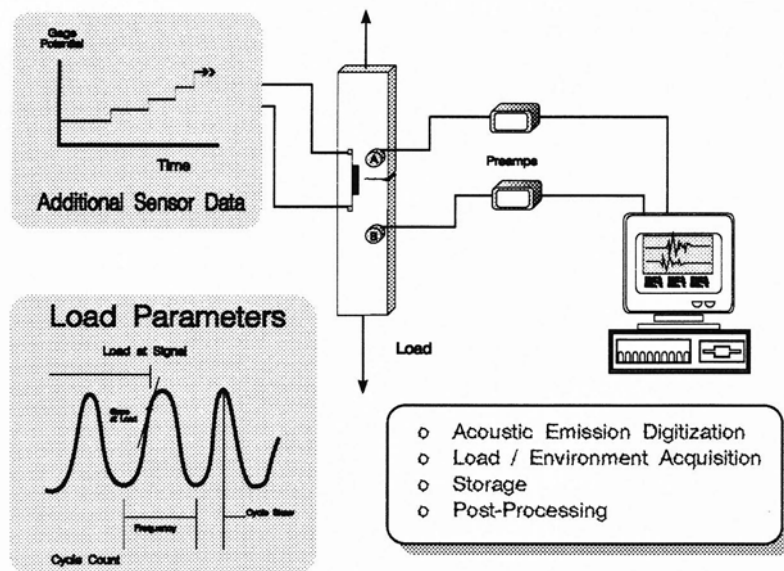


Figure 1. Acoustic emission waveform acquisition and fatigue parameter monitoring during testing.

emission signal. The second is for digitizing and analyzing the load and specimen environment parameters. A schematic is shown in Figure 1. The board being used to acquire acoustic emissions digitizes 2 channels at 8-bit resolution at selectable rates from 1.5 to 25 MHz. 3.25 MHz was used for the examples in this study. There is enough on-board memory to acquire signals up to 32,767 points in length on each of the two channels, which allows for examination of long duration or rapidly repeating events or for extended acquisition at very high time resolution. For this study, the signal sizes of 512 and 1024 points are sufficient to acquire the waveforms detected by the transducers, which have a maximum frequency response below 1 MHz.

External preamps are used to boost the signal amplitude into the digitizer board's fixed input range ($\pm 1\text{V}$). Acquisition is triggered by exceeding a programmable amplitude threshold on one or both channels of the board. When a trigger is detected, signals are offloaded into a temporary 64 KB buffer in the PC's memory. When the PC buffer is full its contents are stored to disk. Signal acquisition rates are about 29 per second for pretriggered signals with the full on-board memory buffer enabled. Pretriggered acquisition requires that the full 32 KB of memory on each channel must be initialized when the board is armed before it will accept a trigger. Rates up to 4 times higher can be achieved by disabling up to three, 8 KB banks of memory to decrease the amount of pretrigger initialization time required. Storage times vary with disk speed. Increasing the number of points per signal increases the storage time in proportion to the size increase. The overall signal acquisition rate with storage on an 80386 computer with storage to fixed disk is about 26 signals per second.

In addition to the waveform acquisition board, a second PC board is used to acquire and process load and other environmental parameters. There are channels available on the board for up to 14 single ended or 7 double ended environmental inputs. This board also contains its own 10 MHz 80186 processor and control program and acts in parallel with the host PC. The operating system is multitasking and its acquisition and processing tasks are time shared. For the cyclic fatigue loading used in this study, the board is programmed to acquire load cycle count, frequency, the load at which emissions occur and parameters which indicate the shape of the fatigue cycle. The derivative of the load at the time of an event is also computed to provide information about whether emissions occur on rising or falling load. The load is sampled at 3000 Hz, and samples are averaged to a slower rate, typically 150 Hz. The high sample rate permits the trigger to be detected. The load averaging reduces the amount of input data and produces the data smoothing necessary to permit summary information to be computed. Load and load slope averages are centered around the trigger point, so the error in the time at which the load samples are taken is of the order of $1/3000\text{ s}$. For random loading conditions, load spectrum information could be acquired instead of the cyclic parameters.

The AE signal acquisition board sends a TTL pulse to the load monitor board whenever it triggers or times out. Upon receiving this signal, the load monitor board program, sends the summary load and environmental parameter information to the calling program on the PC through the computer bus. The parallel acquisition and on-board processing frees the PC to acquire and manage the AE signals optimally, but the time needed to compute the load summary and auxiliary information slows the overall AE acquisition rate, because the processor on the load board has to handle the trigger monitoring, load and parameter acquisition, calculations and data transfer. Current signal acquisition rates with cyclic fatigue load tracking and one or two additional sensor measurements are 10 and 16 signals per second for load tracking with calculations done on a load trace averaged down to 150 and 250 Hz, respectively. The AE monitoring system is operable with and without the load tracking activated.

In addition to tracking load, the load monitor board also monitors a crack growth gage which has been used to obtain the extent of crack advance in relation to generated AE signals. A crack gage, a parallel wire grid, is cemented to the specimen in such a way that the growing crack breaks individual wires and causes a discrete potential change across the gage. Strain gages are being instrumented for a future structural test.

EXPERIMENT

In order to illustrate the capabilities and advantages of the AE data acquisition system the results of two tests are presented, the first test which will be reported was a fatigue crack growth experiment done on an edge notched specimen similar to the one in the schematic in Figure 1. The specimen was a prenotched aluminum lithium alloy plate 1/8" thick 1" wide and 8 in. long. Crack growth was perpendicular to the rolling direction. Load was applied through pins mounted in holes at each end. The specimen was loaded in a hydraulically driven MTS test frame. The test was constant tension-tension fatigue loading at 800 lb with a load ratio of 0.1, and was run at 20 Hz. Monitoring was started after the specimen was precracked. Two AE transducers were mounted on the specimen using acoustic couplant and C-clamps. They were placed at different distances above and below the notch to allow for zone isolation.

The crack grew slowly at first and then accelerated. The crack path was relatively straight, and the crack appeared to be growing under a plain strain condition. When the crack was about 1/3 of the way across the specimen, the crack tip plastic zone size increased (observed as surface dimpling) enough for the crack path to become more tortuous. Crack advance was increasingly rapid in the plastic region.

Based on the relative arrival times, the signals were observed to originate from the crack zone. The only obvious extraneous signals were hydraulic signals which occurred when the test was stopped and restarted so that visual crack length measurements could be taken.

Crack Length and Emission

Plots of the visually measured crack length and the number of AE events versus the time in the fatigue cycling at which AE events occurred are shown in Figure 2. Over 16,000 events were recorded before the specimen broke. The first 10,000 signals were continuously recorded at the same digital threshold level. To simplify presentation, only these points are shown in Figures 2 and 3. Signals were observed on the computer screen as they were acquired. High gain (60 DB) and low threshold (~ 0.06 V) were used to ensure that the lower amplitude slow crack growth events were detected. In the early

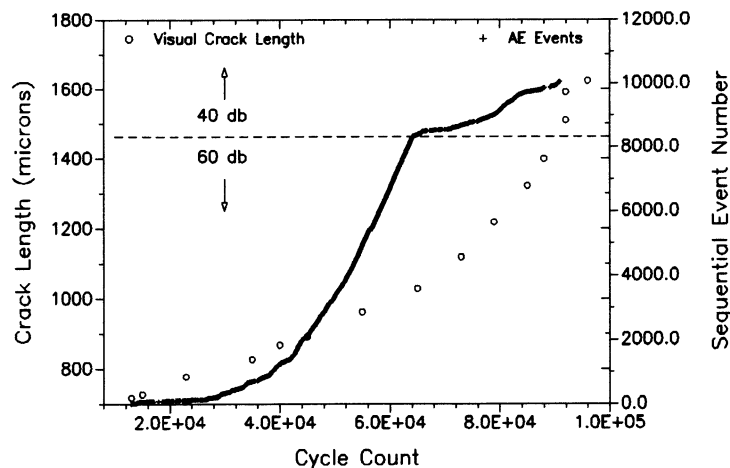


Figure 2. Crack length and the occurrence of emissions during fatigue crack growth.

portion of the test, where crack advance was slow, the signal amplitudes were of low amplitude and occurred more sporadically. As the crack growth rate increased, the AE event rate and amplitude range increased. At 64,000 cycles, the signals were frequently saturating, so the gain level was lowered to 40 DB. The apparent AE event rate decreases abruptly at this point because only signals with 10 times the initial threshold amplitude are accepted for storage. The slope of the plot could be made to look continuous by eliminating the lower amplitude signals from the earlier portion of the curve, but then the slow crack growth would not be easily detectable.

There is a slight knee in the event arrivals at about 80,000 cycles. This corresponds to the onset of crack tip plasticity and rapid plastic growth. Although the crack growth rate continued to increase past this point, the rate of occurrence and amplitude range of events tended to decrease. This trend continued to the point of specimen failure.

The less brittle failure in the plastic region made less noise. The signals also differed in appearance from those in the plain strain fracture region.

Event Cycle Position

The load information for the first 10,000 sequential events is shown in Figures 3 (a) and (b). Figure 3(a) shows the load at which signals occur. The boundary lines at 840 and 105 lb are the maximum and minimum loads in the fatigue cycle. 80% of the events occur at loads greater than 600 lb. During the early phase of the test, although there is a high density of signals at high loads, events occur in other regions of the load cycle. The crack is tightly closed in this region, the signals at other loads are likely to originate from the crack faces rubbing against each other or other closure-related sources. The incidence of low load signals drops greatly once the crack opening is well established.

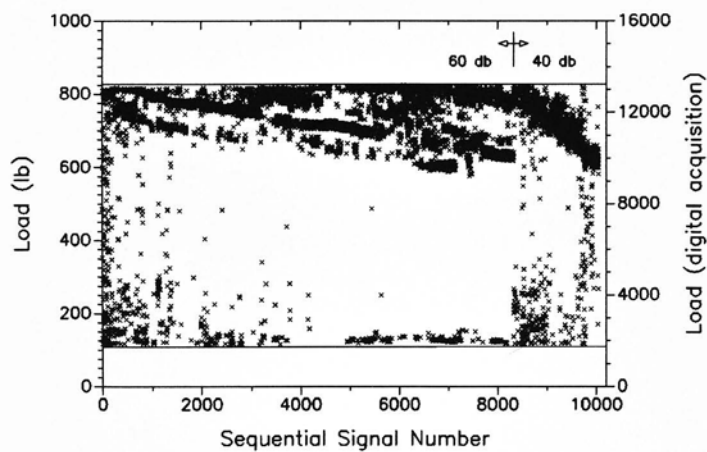
There is an decrease in the load at which events occur over the course of the experiment. This trend is also observed in titanium aluminide fatigue crack growth [2], and the mechanism proposed is that the onset of failure corresponds to a critical stress intensity level. As the crack lengthens, the stress intensity range increases for a constant load range. Thus, the load at which the critical stress intensity is reached becomes lower as the crack advances. The aluminum lithium failure loads are much more scattered than those for titanium aluminide, and events occur in a region spanning an initial level, through to the maximum load. Aluminum lithium is much more ductile than titanium aluminide. The broadening of the failure region may be a processes of slip band and microcrack formation as precursors to macro scale crack jumps.

At the point where the preamplification is lowered to 40 db, there is an apparent rise in the load at signal. The lower amplitude crack jump precursors were screened out by the effectively higher threshold. There is also an increased incidence of low load signals in the plastic growth region. When the ductile failure process begins to dominate in aluminum lithium, the crack path becomes more tortuous. With the higher degree of texture, more interfacial rubbing can occur. With increased crack tip deformation, more closure can occur during unloading.

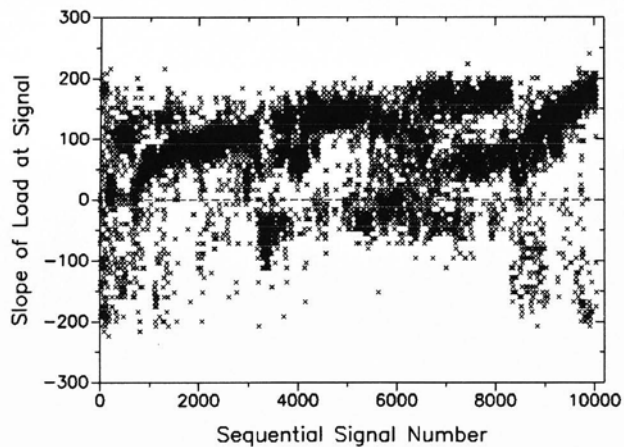
Figure 3(b) shows the unscaled slopes of the load at the time signals were detected. 85% of the load slopes were positive. To aid in signal classification, the slope and load data should be explicitly correlated. Signals occurring at high loads and positive slope are the most reliable signals on which to base a signal processing training set.

Waveform Processing

Results from the second experiment will be used to illustrate a signal discrimination technique which takes advantage of the availability of the high information content in the time domain acoustic waveforms. There are much fewer signals in this test, and so the results of the signal processing are much easier to view and interpret.



(a)



(b)

Figure 3. Occurrence of AE events in respect to the fatigue loading cycle acquisition. (a) Load at which events were detected. (b) Slope of load during signal.

The specimen is a cantilever beam built up of three layers of 1/8" aluminum. It is designed so that a crack originating from a notch in a single thickness (1/8") section can grow at low loads. However, the allowable deflection of the beam is constrained by its mount, so stiffeners were added by gluing and then bolting 2 extra layers of 1/8" aluminum to the unnotched cantilever section.

Two damage processes occur when this specimen is loaded; the crack extends and the glue joints delaminate. The specimen is to be used to evaluate in-situ component cracking, so the existence of an uncharacterized damage process was undesirable. No thicker aluminum was available to produce the equivalent geometry out of a single piece of material, so it was necessary to separate the damage mechanisms.

To evaluate the separability of the cracking and delamination damage mechanisms, an additional test was run on an unnotched specimen of the same geometry. Only the delamination damage mechanism occurs on the unnotched specimen.

The two beams were slowly fatigued in a screw driven Instron test frame, and time domain AE waveforms were collected during each of the tests. 110 signals were collected during the flexure of the notched specimen, and 140 signals were collected for the unnotched beam. The results of the two test were combined, preprocessed, and cross correlated with each other in the manner outlined in [2, 3]. The correlation results are show in Figure 4. All signals are correlated against all other signals. The beginning of the correlation matrix is at the upper left corner (A). The darkness of any region indicates the level of correlation of the waveforms corresponding to the coordinate points. The printable grey levels are limited, so to some degree, the correlation level in this view is also keyed to blackness density. The results are symmetric about the diagonal, which itself has a 100% correlation level (signal 1 correlated with 1, 2 with 2, etc.). Only the upper triangle is computed. The lower triangle is filled in for reference. Regions A and C are pencil lead breaks performed on each of the specimens prior to loading. The breaks in A correlate with each other, as do the breaks in C and the crossed region between the two. The breaks do not correlate well with the AE signals during testing. The region between A and C is the correlation of signals on the notched specimen. There is a high degree of correlation among most of the signals on the notched specimen from A to B. The region from B to C exhibits correlation on a more local scale. This region of the test corresponds to the last loading cycles on the beam where the crack growth was becoming increasingly plastic. The plastic crack growth mechanism does not match the more brittle mechanism

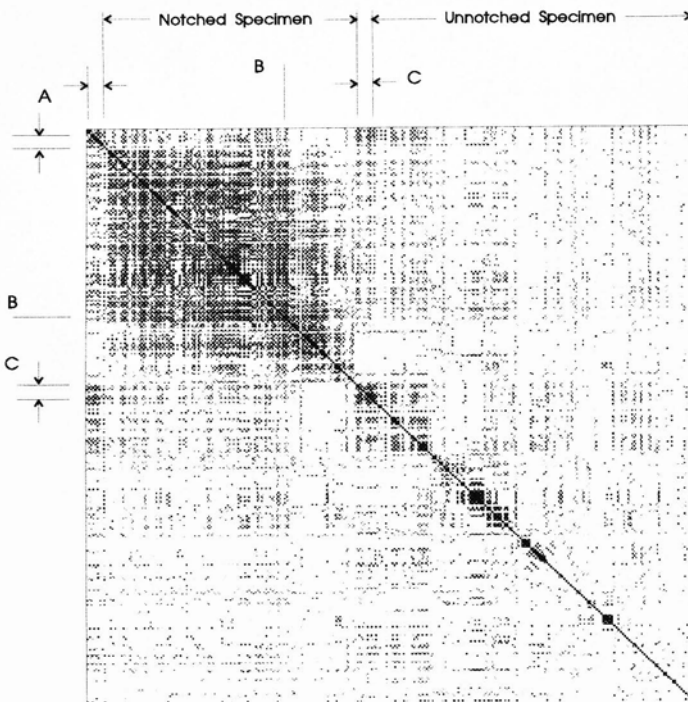


Figure 4. Correlation matrix showing the relationship between signals generated during fatigue of notched and unnotched laminated aluminum specimens.

occurring early on in the test. In the region just prior to C, the damage region had become more of a plastic hinge than a sharp crack, only local correlation was exhibited here.

The region past C is the correlation of the unnotched beam signals, and should contain only delamination events. The unnotched signals correlate with each other only on a local scale (dark regions near the diagonal), and do not correlate with the signals generated by the notched fatigue specimen. From these results, it is inferred that most of the signals generated from the notched specimen are cracking signals, and that the few delamination signals that are present do not fall into the characteristic crack category. The crack in the notched beam is clearly the "weak point" in the specimen. Most of the energy is absorbed in this region as crack growth, and the stiffened region undergoes less deflection than that of the unnotched beam.

CONCLUSIONS

A compact PC-based acoustic emissions monitoring system with the capability of acquiring and storing time domain AE signals in real time has been developed for investigating fatigue crack growth. The system can also acquire load and other parameters which define the load environment of the part and can be used to isolate and validate characteristic crack signals.

Signal processing techniques can be applied to the time domain signals to discriminate damage mechanisms.

Load information obtained during AE monitoring can provide insight into the micro-mechanical failure mechanisms which occur during crack growth.

The usefulness of acoustic emissions monitoring on components which experience ductile failure may be limited because of the lower rate and amplitude of signal generation.

REFERENCES

1. J.B. Boodey, D. Granata, W. Scott, I. Perez, And M. Wilson, "Acoustic Emissions From Microindentation Fracture Toughness Tests," Progress in Quantitative Nondestructive Testing, Ed. D. Thompson and D. Chementi, Plenum 1991.
2. D. M. Granata, W. R. Scott, J. Davis*, E. U. Lee
J. B. Boodey, P. Kulowitch, "Acoustic Emission Monitoring of a Fatigue Crack," Progress in Quantitative Nondestructive Testing, Ed. D. Thompson and D. Chementi, Plenum 1991.
3. D. M. Granata, W. R. Scott, Eun U. Lee, Jon Davis, "Acoustic Emission Potential in Intelligent Manufacturing: A Sample Problem," Proceedings of 5th IEEE International Symposium on Intelligent Control, Ed. Alex Meystel, Jayantha Herath, Steve Gray, IEEE Computer Society Press, 1990.